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Wave Energy Resource Evaluation and Characterisation for the Libyan Sea

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Abstract

The study focuses on a high resolution coastal assessment for the Libyan Sea at the South-West Mediterranean. To date majority of information for the area, are based on large scale oceanic models with coarse resolutions not adequate for nearshore assessments. This dataset and analysis provides an in-depth wave energy resource assessment and detail dissemination of sites according to their metocean characteristics. Identification for wave energy is based on the database constructed, allowing the quantification of energy levels and resource implications at sites.

Mean values of wave heights around the coastlines are $\approx 1m$, though high storm events exceed $5m$ at several areas. Highest wave energy resource are located at open coastal areas, with energetic months reaching up to 10 kW/m . Low energy seasons are throughout summer months, where energy content is reduced threefold. The resource can be classified as low, however coefficient of variation suggests a predictable resource with extreme events not expected to surpass $10m$.

Although, resource is not as energetic as open oceanic regions the low variations may assist wave energy as a supporting renewable energy option. Assessing the wave climate around the coasts for a long period of time, also provides confident and robust suggestions on the selection for wave energy converters. In addition, the lower extreme events are expected to reduce potential installations costs by lowering structural expenditure and strengthen-

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ing works to facilitate operation at milder environments.

Keywords: Wave Energy, Numerical Wave Modelling, Wave Power, Extreme Value Analysis

1. Introduction

Countries world-wide are exploring increased adaptation of renewable energy in order to achieve energy independence and fiscal benefits [1, 2, 3]. South Mediterranean countries are exposed to high levels of wind and solar resource, wave energy is a renewable high density resource that is often overlooked.

North African countries have been increasing their interest into renewable energy, this study presents an extensive wave power assessment, investigating for the first time the opportunities that may arise from wave energy. The 35 years nearshore database hindcast allows to present long-term evolution of wave conditions, climate variability, and extremes given for the areas. Such information are important for future wave energy deployment but can also be used in coastal defences, and environmental studies.

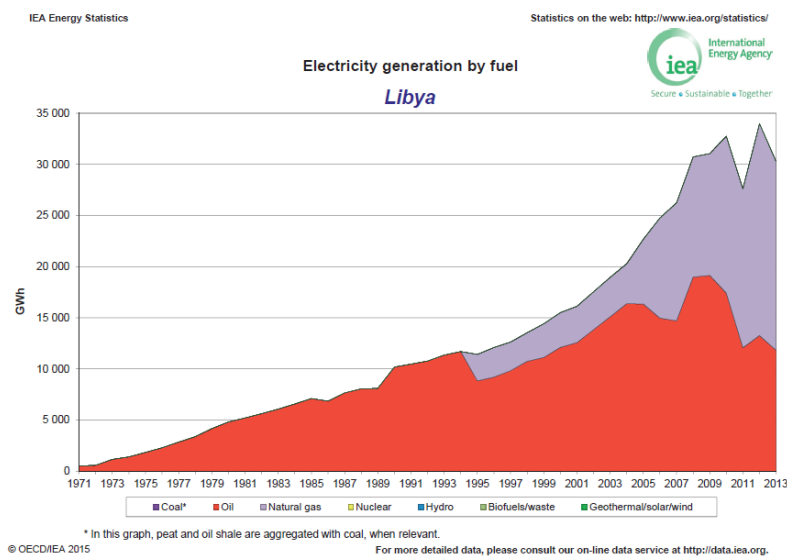


Figure 1: Libyan energy mix electricity contribution per fuel as given by the International Energy Agency as in 2013 [4]

Libya is a developing country whose production is dominated by fossil fuels. Lately steps were introduced for integration of renewable technologies in the electricity mix, mostly onshore wind and photovoltaics, both though at infancy levels. Due to the structure of electrical grids opportunities exist for renewable energy (RE) development through a localized de-centralised approach, reducing infrastructure necessities [5]. The increasing trend of energy imports has underlined the necessity for supply diversification and renewable energy deployment consideration. Nowadays, financial schemes are provided by European Development Bank (EDB) and World Bank Group (WBG) for development of clean energy projects.

As seen in Fig. 1 Libya is completely dependent in electricity by fossil fuels. More specifically, for the year 2013 Libyas electrical consumption was at 24.58 TWh with the majority of electrical supply originating from oil (11.8 TWh) and gas (18.4 TWh) products. This dependency is based on other countries that are oil producers and underline the necessity for energy diversification. Future plans include the interconnection of neighbouring countries (Libya, Algeria, Tunisia and Italy) in an attempt to maximise commercial and geopolitical cooperation of energy exchange (see Fig.2). This provides potential opportunities for the exchange of surplus electricity by renewable energies.



Figure 2: Plans for connection lines between the North African counties as found in [5]

Libya is a country recovering from internal conflicts and major geopolitical

35 events, while the level of maturity for energy technologies and companies is
36 not as competitive as in Europe. Several African countries are considering
37 the interconnection of the electricity grids in the continent, as a way to reduce
38 external dependencies and assist to the development of the region [6]. Thus,
39 significant opportunities arise by the ever-rising energy consumption in the
40 emerging countries of the African continent.

41 Libya has an open dialogue and discussion of potential development of
42 different renewable technologies as discussed in Mohamed et.al. [7, 8]. In
43 that discussion immediate usable technologies identified are solar, photo-
44 voltaic and wind. From an extensive interview with policy makers, energy
45 companies and public awareness/acceptance, Mohamed et.al. [8] concluded
46 that applicability and acceptance of RE is at high levels. Concerning wave
47 and tidal energies, Libyan policy official consider them viable at 23%, and
48 company generators at 18%. Furthermore, above 80% of both industry and
49 government official admit that RE can satisfy the increasing energy con-
50 sumption and assist the financial developments, more information on the
51 interviews can be found in Mohamed et.al. [8].

52 The inter-dependent nature of wind and wave resources, allow further RE
53 integration and ability to for the electrical grids to absorb higher levels of
54 renewable electricity [9, 10, 11]. Allowing development of decentralized grids
55 that have lower cost of energy and can act as a viable solution for economic
56 growth.

57 The study aims to contribute and underline the opportunities that exist
58 for wave energy production in Libya. Long-term data produced by a val-
59 idated coastal numerical model, which run over 35 years are subsequently
60 used for extensive climate, resource and a site classification analysis. Infor-
61 mation on model set-up, calibration, boundaries, can be found in Lavidas
62 et.al. [12, 13].

63 This study is separated in the following sections: Section 2 presents in
64 brief the wave model used and the information extracted, and discusses gap
65 of knowledge in the region. Section 3 provides the wave climate and power
66 variations. Several extracted locations are examined in terms of wave charac-
67 teristics and power. Annual and monthly variations are presented, alongside
68 a detail site characterisation based on the joint distributions of metocean
69 characteristics. The extreme value analysis is based on the dataset and pro-
70 vides return periods that may affect wave energy deployments and offshore
71 activities. Section 4 discusses the findings, and addresses the opportunities
72 within the region, based on results of the analysis.

73 2. Material and Methods

74 Simulating WAVes nearshore (SWAN) is a third generation spectral phased-
75 average model used for wave studies [14]. The wind input is provided by
76 NCEP and the Re-Analysis package of the CFSR dataset, 1-hour time in-
77 tervals [15]. The model was initiated for the Mediterranean Sea and for
78 subsequent meshes for a duration of 35 years from 1980-2014. A two way
79 nested scheme was used, the Mediterranean domain had a spatial resolution
80 0.1° , Libya domain was examined under a finer mesh with resolution 0.025° .
81 A detail validation has been presented in Lavidas et.al. [12, 13]. The calibra-
82 tion and coefficient tuning took into account the higher temporal resolution
83 of the wind product. The calibration results tested two different formulations
84 for wind growth, with the selected scheme providing good correlations, low
85 biases and reduced scattering.

86 The wind scheme is based on formulations by Komen [16] with a linear
87 growth coefficient activated [17]. Bottom friction, depth breaking, refraction,
88 diffraction processes all are used to account for wave interactions. Triads are
89 solved with the Eldeberky method [18], and quadruplets are activated in a
90 semi-implicit way.

91 Direction has been subdivided into 25 intervals while the frequency is
92 discretised in 30 bins, the lowest initial wave frequency used is set to 2 seconds
93 while the highest is 28 seconds and they are distributed logarithmically ($\Delta f =$
94 $0.1f$). The selection and range of frequency and directional bins, has a
95 direct effect on the computational resources, while often times an increase
96 in the parameters does not translate into improved performance [19]. The
97 coordinates are Spherical and have been extracted by ETOPO-1 [20] and
98 bathymetry domains were constructed using bi-linear interpolation.

99 The final database was compared with buoys measurements and other
100 state-of-the-art models run in the region, that also shared same buoy data.
101 The resulted dataset found improvements over a compared oceanic models,
102 with lower root-mean-square-error (rmse) values and biases for our dataset.
103 However our model also recorded over-estimation of wave parameters for very
104 low resource levels, something that is expected in numerical wave models [21].
105 In addition, our datasets spatial wave energy distribution was also compared
106 to a high resolution unstructured model for the Aegean, finding similar "hot-
107 spot" distribution and obtaining similar generation correlation coefficients
108 for same buoy locations [13].

109 Numerical wave models have been used for the Mediterranean Sea, with

oceanic models whose resolution is not often adequate to resolve coastal areas, see Table 1. Majority of studies are based on oceanic models with spatial resolution hindering extrapolation of results to coastal areas, as discussed in Canellas et.al. [22]. For the Libyan Sea no high resolution coastal information exist.

Table 1: Implementation of Mediterranean Models

Region	Study	Model	Period (years)	Spatial Resolution	Parameters
Mediterranean	[23]	WAM	10	$0.5^\circ \times 0.5^\circ$ & $0.25^\circ \times 0.25^\circ$	Waves, Wave Climate
Mediterranean	[24]	WAM	44	$0.5^\circ \times 0.5^\circ$	Waves, Wave Power
Mediterranean	[25]	WAM	10	$0.1^\circ \times 0.1^\circ$	Waves
Mediterranean	[26]	WAM	2	$0.1^\circ \times 0.1^\circ$	Waves
Mediterranean	[27]	WAM	10	$0.625^\circ \times 0.625^\circ$	Wave Power
Mediterranean	[28]	WW3	35	$0.12^\circ \times 0.09^\circ$	Wave Power
Mediterranean	[12]	SWAN	35	$0.1^\circ \times 0.1^\circ$	Waves, Wave Power

Majority of initial studies in the Mediterranean including [24, 25], delivered wave parameter data. Since 2010 though examination of the wave energy resource, usefulness and opportunities within have spurred dedicated studies for wave power [27, 28, 12]. With models both large and coastal scale, at high resolution and delivering long-term records with usual range of data $\approx 10 - 35$ years.

Wave energy is derived by the wave height (H_{m0}) and so-called period energy (T_e) and/or peak period (T_p) that the local resource offers. The energy contained within waves expressed in W/m , corresponds to the energy per crest unit length. In SWAN energy components are computed with a formulation appropriate for the realist representation of resource. Over the summation of very different wave frequencies (f) and directions (θ).

$$P_x = \rho g \int \int C_{gx} E(f, \theta) df d\theta \quad (1)$$

$$P_y = \rho g \int \int C_{gy} E(f, \theta) df d\theta \quad (2)$$

where $E(f, \theta)$ the energy density spectrum over an x (longitude) y (latitude) system. C_g are the components of absolute group velocities, water density (ρ), g gravitational acceleration. Total wave power is estimated in kW/m :

$$P_{wave} = \sqrt{P_x^2 + P_y^2} \quad (3)$$

131 The study contributes to the offshore community, with a high resolution
132 wave database and analysis. All extracted locations represent easily acces-
133 sible site, enhancing analysis outreach since no information from buoys or
134 regional models exists for such a long period in Libya. With most model
135 data being hindered by non-adequate resolution at these depths and dis-
136 tances from shores, the locations considered and their respective origins are
137 presented in Table 2.

Table 2: Coordinates and depth information of the extracted locations

Location	Longitude	Latitude	Depth (\approx m)
Libya1	14°20"	32°75"	30-35
Libya2	21°77"	33°00"	130-150
Libya3	22°45"	32°90"	30-45
Libya4	25°05"	32°00"	40-50
Libya5	17°85"	30°90"	20-30

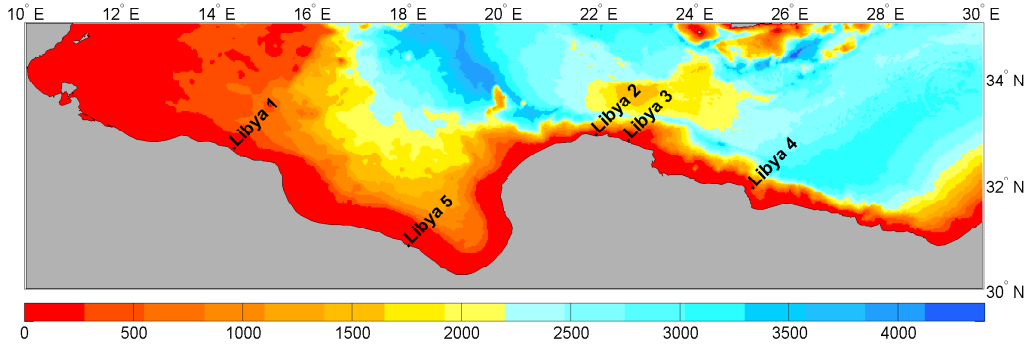


Figure 3: Locations and Depth of domain in meters

138 3. Results

139 Libyan points examined are located in both the West and East Side of the
140 coastlines, providing a representation of expected resource and fluctuations
141 along the coasts. Point selection was based on H_{m0} and wave energy maps
142 of previous hindcast studies by the authors. Libya 1 is located at the East
143 coasts near the city of Al-Khums, Libya 2 is between the city of Al Hamamah

144 and Susah, Libya 3 is on the North West of the city of Dernah. Libya 4 is
 145 on the far east side of the Libya coasts on the East of Tubruq and Libya 5 is
 146 at the located at the Gulf of Sidra East off the town of Surt.

147 Highest values of mean and maximum H_{m0} are recorded in Libya 2-4,
 148 followed by Libya 1. Lowest levels of both mean and maxima are encountered
 149 in Libya 5. This was expected since Libya 5 is located at an encapsulated area
 150 at shallow depths, with surrounding land masses reducing incoming resource.
 151 Interestingly Libya 1, placed at an exposed region receives significant levels
 152 of wave height, eastern location are exposed similar trends in magnitude
 153 and trend annually. Maximum values differ significantly for locations, mean
 154 exposed resources remain the same for all areas within the range of 0.75-0.85
 155 meters (see Fig. 4).

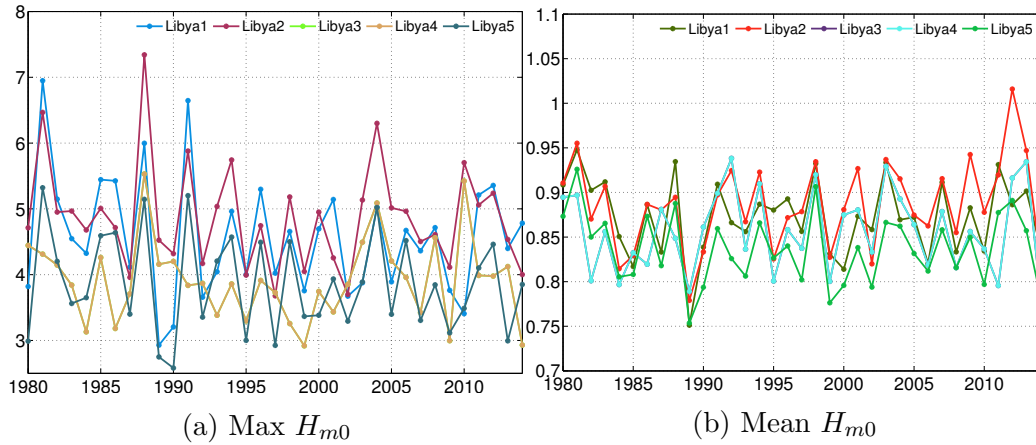


Figure 4: Wave characteristics of locations

156 Greater differences in mean and maximum values of H_{m0} exist between
 157 records from the hindcast. Libya 2 has an average difference of wave height
 158 around 2.5 meters (maxima) and 0.30 m (mean) (see Fig. 4). While this
 159 suggests the energy content will not be as high at the first location, conditions
 160 that potential wave farms are exposed will be significantly less reducing the
 161 capital expenditure.

162 Wave resource while milder in South Mediterranean it can still play an
 163 important role in both the production and coverage of renewable variability.
 164 Wave energy is directly correlated to wind for wave generation and
 165 propagation, and indirectly to solar through environmental interactions of
 166 precipitation.

167 Furthermore, winds blowing over the area affect locally generated waves.
 168 Waves can act as "storage" carrier of energy content which has temporal dif-
 169 ferences in comparison with wind [29]. This is expected to be an important
 170 component since inter-connectivity of resources (wind and waves), can act
 171 complementary minimizing discrepancies in expected production, and reduc-
 172 ing to some extent the necessity for infrastructure that can accommodate
 173 increased renewable energy [30, 31, 32].

174 Coefficient of Variation (CoV) reveals the level of variability of wave
 175 energy across the area, combination with individual locations maxima and
 176 means allows identifying potential locations that have high resource and min-
 177 imum variation of wave energy. This ensures that the potential energy pro-
 178 duction by WECs will be uninterrupted and deliver smoother operation and
 179 energy production throughout their lifetime operation.

$$CoV = \frac{\sigma}{\mu} \quad (4)$$

180 The CoV in Fig. 5 is based on the estimation of the P_{wave} mean (μ) and
 181 standard deviation (σ) values (see Eq. 4), the scale of the figure has been
 182 scaled to display the region with the highest levels. This allows examination
 183 of seasonal, intra-annual, and decadal variations for both significant wave
 184 height and period. Fluctuation annually and overall are adequately resolved
 185 over a long-term context, which is suggested by previous protocols and studies
 186 that propose at least 10 years data to be used for characterization [33, 34].

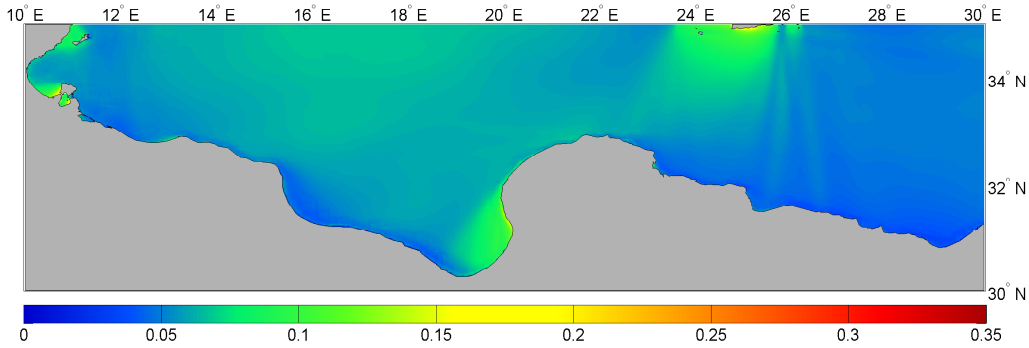


Figure 5: CoV of Wave Energy over 35 years for the Libyan coastlines (scaled down)

187 Highest CoV levels encountered at Gulf of Sidra (Khali J Surt) with
 188 values ranging from 0.1-0.15 (see Fig. 5), since the locations are placed in an

189 encapsulated environment and the propagated resource is reduced by bottom
190 interactions and coastlines. Remainder of coastlines are exposed to low levels
191 of CoV.

192 In the case of Tunisia, the Southern part in the border with Libya,
193 presents similar levels of CoV and more specifically at the peninsula of Jerba
194 at the Gulf of Gabes. The inner coastlines are affected by refraction, shoal-
195 ing, and depth breaking effects characterising interactions between sudden
196 changes and areas behind land masses, accounting for higher CoV values.
197 Turning orography from North to South of the Libyan coastline affects the
198 final levels of energy flux that reach the areas, with complex areas being
199 un-desirable for WEC applications. This ensures that WEC farms will be
200 able to deliver predictable amounts of energy in their annual yields. The
201 change and variability of wave power apart from the information that can be
202 extracted from Fig. 5, can also display the CoV expected.

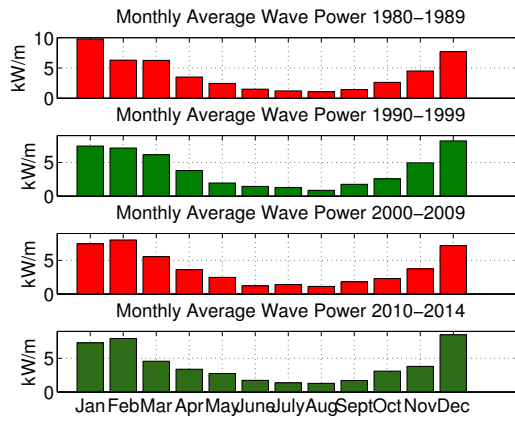
203 From Figs. 6-7, distribution of monthly wave energy for selected locations
204 as well as overall monthly average are estimated. In all cases summer months
205 present the lowest values, as is to be expected. Highest levels of resource are
206 found in the autumn and winter months with a slow decrease over the spring.

207 More specifically for locations 1–4 have similar distribution of monthly
208 mean energy, with Libya 1 expressing a maximum value of wave energy of 8
209 kW/m (overall) and minimum ≈ 1 kW/m, see Fig. 6. Libya 2-4 have the same
210 levels of magnitude in wave energy with overall maximum resource located
211 at 10 kW/m and the lowest at 1kW/m, see also Fig. 6. Libya 5 as discussed
212 in the wave height analysis has the lowest incoming wave parameters with
213 the highest frequencies thus reducing the incoming flux. This is evident in
214 Fig. 7 where the overall maximum is around 6.5 kW/m while minimum value
215 is 1.5 kW/m. The decadal analysis of the months also exhibit that annual
216 monthly averages deviate as well.

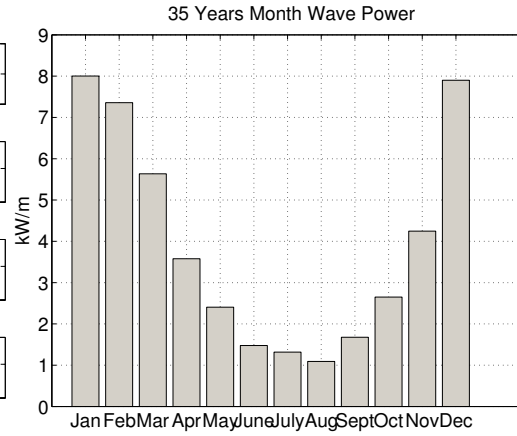
217 Spatial distribution of wave power for the region is presented in Fig. 8.
218 Following the energy analysis for the locations, highest resources are met on
219 the North-East coast, with intermediate depth wave power close to $8(kW/m)$
220 (Locations 2-3). The Gulf of Sidra (Khali J Surt), and West areas near the
221 Gulf of Gabes have the lowest resource overall.

222 3.1. Wave Energy Development Index (WEDI)

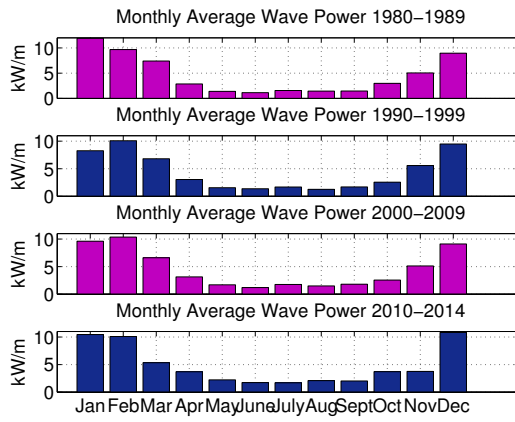
223 In order to quantify and assess potential sites for future research and
224 WECs application, wave energy distribution must not be the only criterion.



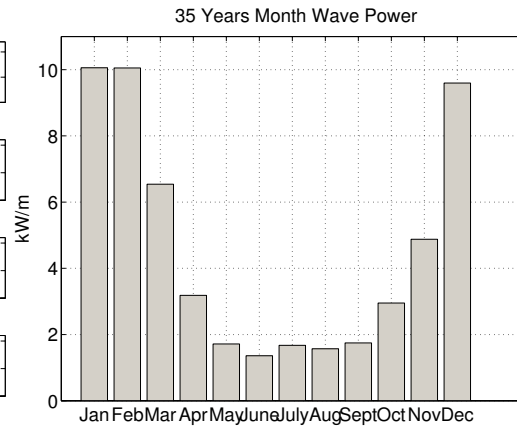
(a) Libya 1 decades



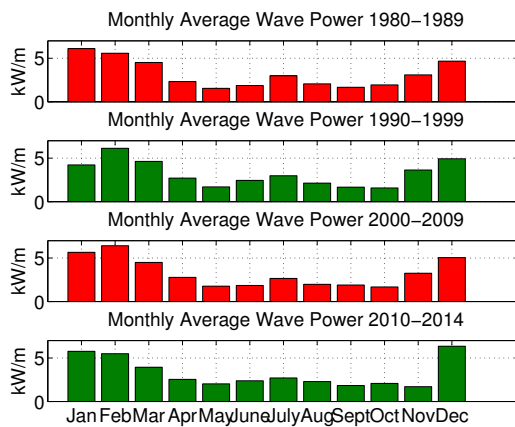
(b) Libya 1



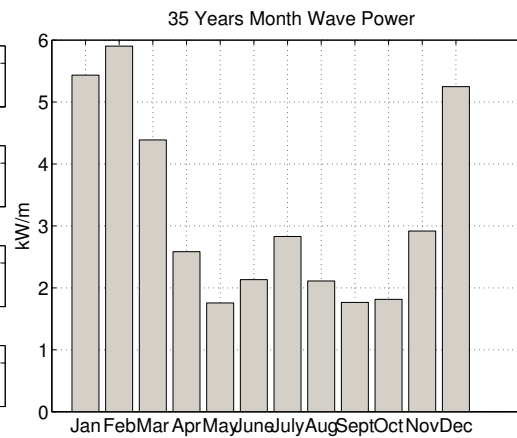
(c) Libya 2 decades



(d) Libya 2



(e) Libya 3 decades



(f) Libya 3

Figure 6: Wave Characteristics of locations 1-3

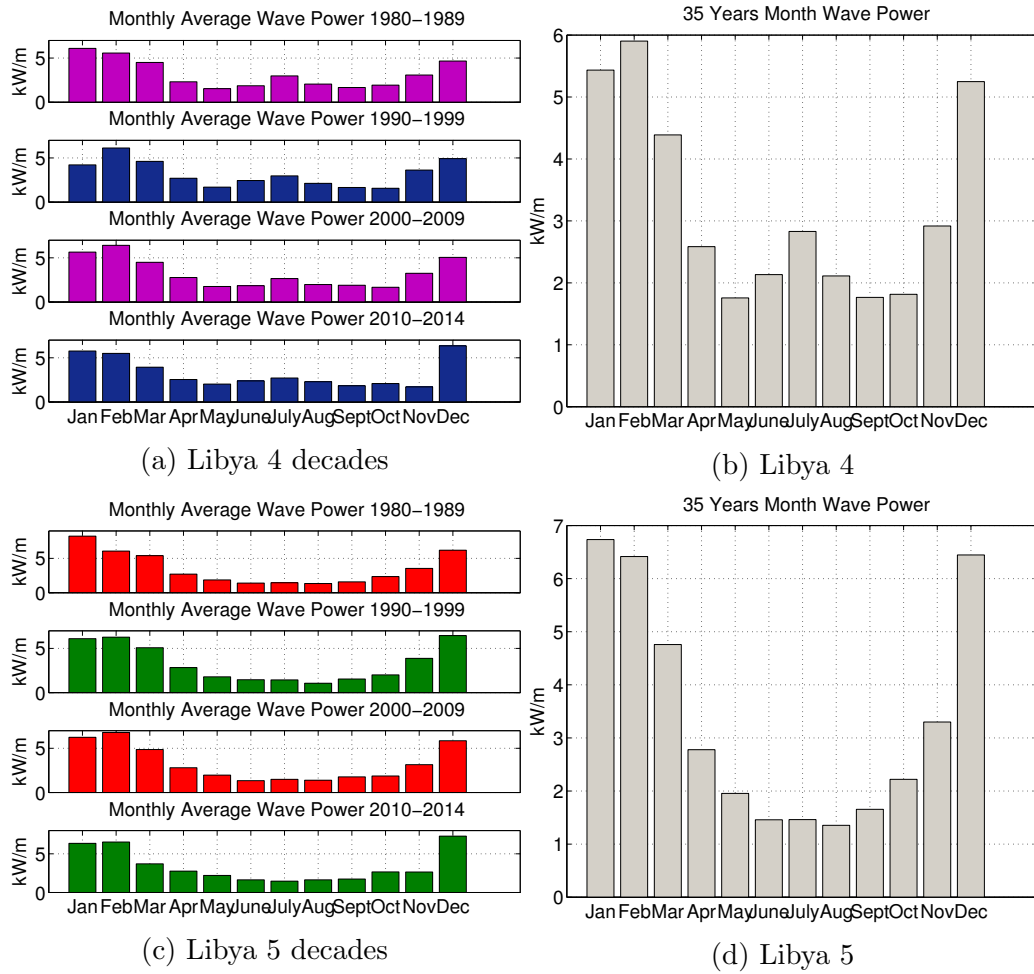


Figure 7: Wave Characteristics of locations 4-5

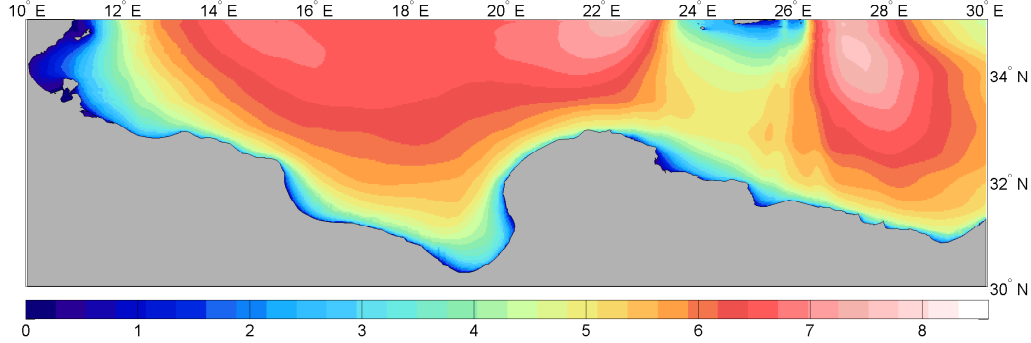


Figure 8: Wave Power content (kW/m) for Libyan Sea through overall hindcast period

225 Metocean conditions do not only affect wave energy flux but also have di-
 226 rect implications on survivability structures deployed. Wave Energy Devel-
 227 opment Index (WEDI) as presented by Hagermann [35] and Akpinar et.al.
 228 [36], associates effects of mean ($\overline{P_{wave}}$) and maximum wave power (J_{wave})
 229 thus including storm events, see Eq. 5. WEDI provides insight on potential
 230 dangers and interactions that harsh events can have on WECs and offshore
 231 structures. While, it is not the sole decisive factor, the index in combination
 232 with the mean energy content and extreme value analysis can assist in the
 233 proper sitting selection for wave energy converters, reduce infrastructure and
 234 maintenance costs.

$$WEDI = \frac{\overline{P_{wave}}}{J_{wave}} \quad (5)$$

235 The Wave Energy Development Index (WEDI) shows the potential of
 236 wave energy at a site while also reveals the level of danger for a location
 237 (area-region), establishing a "cost-to-benefit" approach taking into account
 238 potential risks with the local conditions in regards to energy levels. The
 239 index has a range from 0-1, locations with 1 have the harshest events that
 240 can affect the survivability.

241 Spatial distribution of the WEDI index over the 35 years hindcast is
 242 presented in Fig. 9, the irregularities of the coastline e.g. small gulf and
 243 turning areas have an effect on the way the final energy reaches the shores.
 244 Such areas are easily identified, and WEDI acquires values up to 0.08. At
 245 shallower locations less than 10m the index acquires higher values, since the
 246 max over the mean often mean "harsher" conditions. Areas near shallow

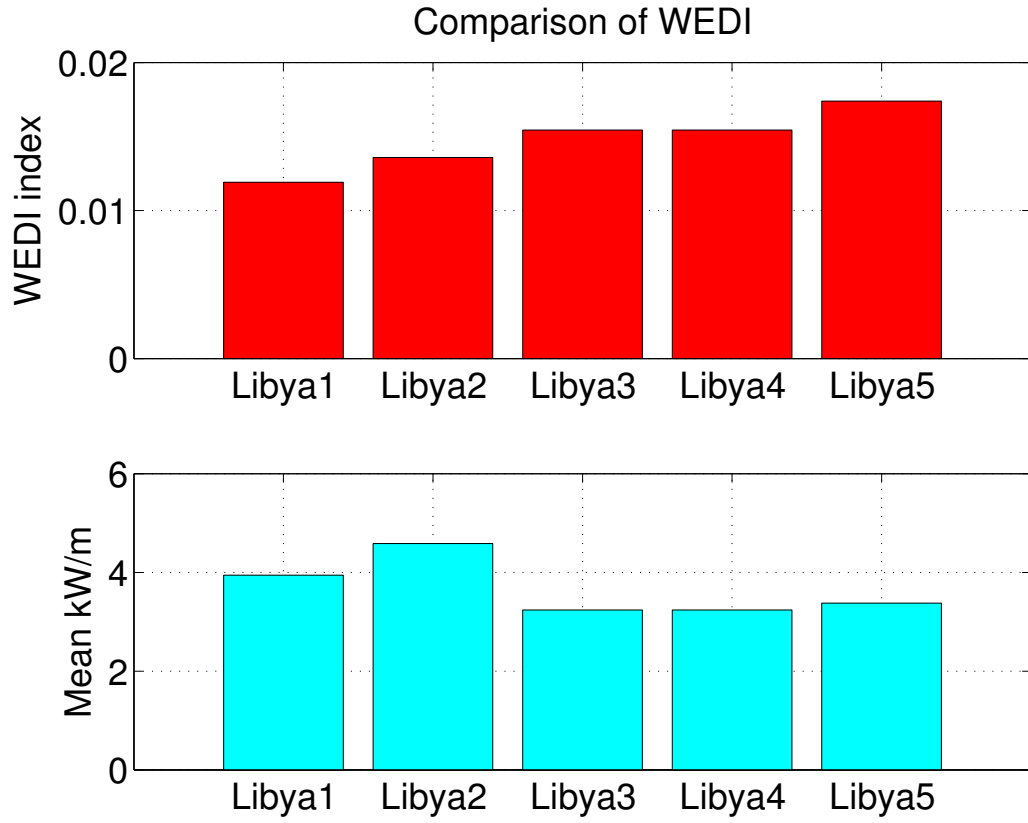


Figure 9: Wave Energy Development Index for the Libyan coastlines for the 35 years hindcast (reduced)

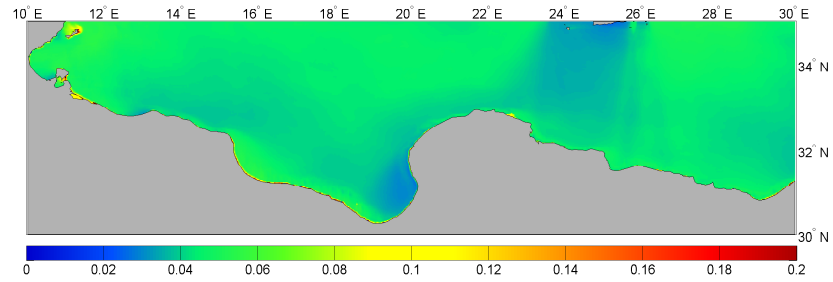


Figure 10: WEDI and mean resource encountered for the Libyan investigated locations over the 35 years hindcast

247 regions reach values of 0.2 such an example can be easily seen in the North
248 West region of the map, at the Sharqi island.

249 From the extracted locations Libya 5 obtains the highest index, thus
250 amongst these locations it is the least favourable (see Fig. 10). On the other
251 hand Libya 1-2 are ranked as the most promising sites, with higher levels of
252 resource constant over time and lower WEDI, this ensures predictability. In
253 a sense WEDI provides preliminary information about "harsh" events and
254 helps us consider some initial levels of capital required.

255 However, when wave farms are be deployed the authors believes that an-
256 other important element is imperative to quantify. That is the investigation
257 of extreme value events. This ensures that effects of extreme return peri-
258 ods on locations provide complete information about the dangers, potential,
259 infrastructure work required.

260 3.2. Wave energy site assessment

261 To assist in the informative decision on site classification, the bivari-
262 ate (joint) distribution of H_{m0} and period are examined. The wave period
263 taken into account in the classification in the energy period T_e , which is
264 directly used in most WEC power matrices [37]. The number of occur-
265 rences of the coupled data provide insights on "dominant" wave characteris-
266 tics height/frequency for each location.

267 In Fig. 11, the hindcast is used to provide with an overview of seastate
268 characteristics. Libya 2-3, locations which are fairly close (see Fig. 3) have
269 similar descriptions. Dominant characteristics describing the points express
270 H_{m0} from 0.5-2, T_e ranges from 4-8 sec. Although, higher records over 7
271 meters for both points are found, they are less than 1% of total time (Libya2)
272 and less 0.5% for Libya 3. Libya 1, also presents similar patterns for wave
273 occurrences, with most common instances of 0.5-2 m H_{m0} and up to 7 sec. It
274 maximum values over 7 m represent less than 0.3%. Libya 4 shows a slighter
275 increase of H_{m0} occurrences, with a good number present to heights from
276 1.5-3 meters. Libya 5, which as seen is surrounded by land masses, has most
277 common wave periods up to 4-6 sec and H_{m0} mostly from 0.5-1.5m.

278 Analysis of the bivariate wave distribution indicates that a wave energy
279 converter should have operational characteristics for low magnitude condi-
280 tions. Operational modes should cover a cut-in (start of production) for H_{m0}
281 between 0.5-1 m and high frequencies (low periods 2-7 sec). Rated power
282 should be reached within 1.5-3m, allowing consistent performance. While,

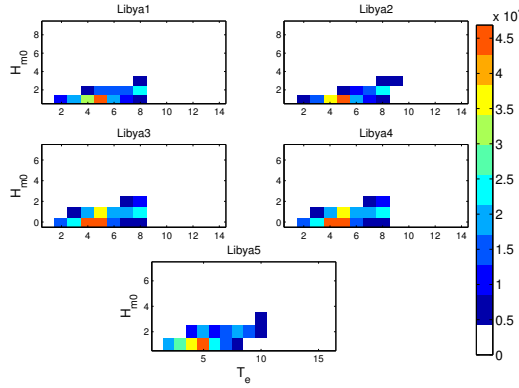


Figure 11: Occurrences

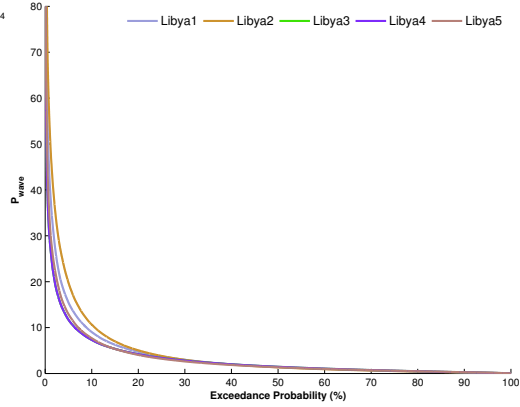


Figure 12: Exceedance probability P_{wave}

283 higher values of H_{m0} are present in the locations, i.e. over 5m, they repre-
 284 sent a small number of occurrences, thus WECs achieving rated production
 285 during such intervals are not suitable.

286 The most commonly found content of wave power for each location, can
 287 also be summarised in the exceedance diagram, see Fig. 12. Libya 2 presents
 288 the highest resource P_{wave} amongst the locations, while Libya 4 the lowest.
 289 The highest probabilities of wave power (kW/m) are under 10 kW/m . The
 290 analysis considers only the resource levels of the region. However, it is im-
 291 portant to note that in the implementation of WECs in the aforementioned
 292 areas, additional information such as directions and spreading are vital. For
 293 example in our domain Libya 2 which has been identified as the most prom-
 294 ising has a wider range of incoming direction predominately from the North
 295 West with higher intensities. On the other hand, Libya 4 has almost all
 296 its wave originating from the North West, indicating that a perpendicularly
 297 North facing device would enhance production.

298 Wave energy production thus depends not only on the bivariate distribu-
 299 tion, but also on the directionality of the resource. In terms of desired direc-
 300 tion, this will depend on the selection of the devices. Some WECs favour a
 301 perpendicular facing approach to the dominant wave direction, while other
 302 devices can utilise a higher number of direction. Such operational character-
 303 istics should be taken into account with the bivariate distribution, in order
 304 for energy production to be optimised. However, up to now most available
 305 information on wave energy production are limited to the bivariate sea states
 306 for production [38]. In order to quantify the directional effects additional in-

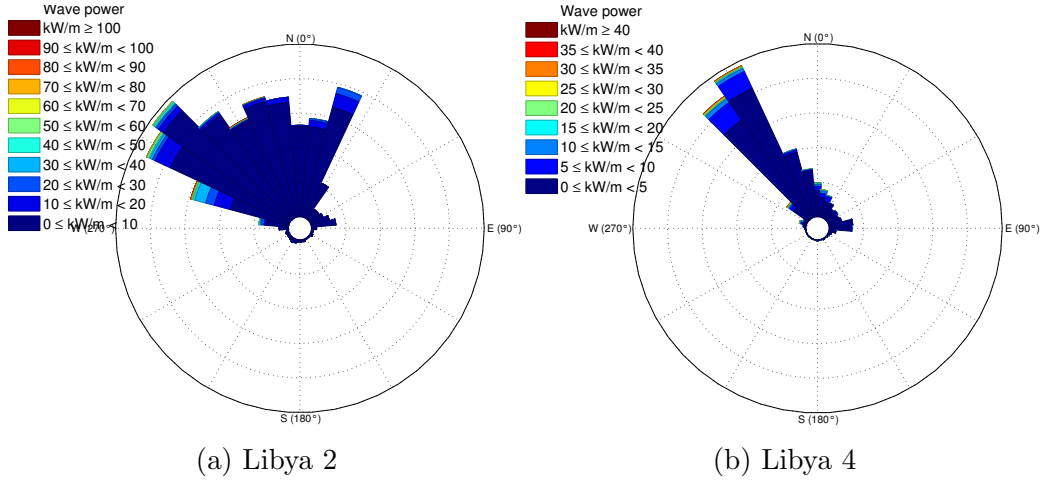


Figure 13: Characteristic wave roses for P_{wave} and direction

formation have to be shared with the international community. Even with the knowledge of directional effects more specialised analysis are needed.

3.3. Extreme Value Analysis

Asides classification of wave energy content and metocean conditions, another important consideration are the expected extreme return periods. Assessment of extremes adds significantly to structural considerations for WECs and offshore activities. Desirably the length of appropriate datasets, should not be less than 20% of the desired return value. For example if a 50 year period is investigated at least 10 years of data should be available [33, 39]. The hindcast H_{m0} of our model is used for an extreme value analysis (EVA) with use of the Peak-Over-Thresholds (POT) and Generalised Pareto Distribution (GPD) [40].

The data constitute approximately 35 years (420 months), with hourly recording ($> 307,000$ hours). The data have been prepared and filtered with threshold ensuring that the final difference of event ensuring data to be identically independently distributed (i.i.d). Common practises suggest a time-frame within 2-4 days to ensure independence, [40, 41].

In order to filter and decluster the current database an appropriate threshold is set, based on the 99th percentile of H_{m0} . The choice took into account the available data and record its effects of the final data size. It is important to note that if a high threshold is set, to a low temporal timeseries the final new dataset may lead to poor statistical fits [42, 43]. Large scale datasets

329 have used a 98th [44] and 99.5th percentile [22]. Length of our dataset suggests
 330 that the 99th percentile would be appropriate to reduce the timeseries.

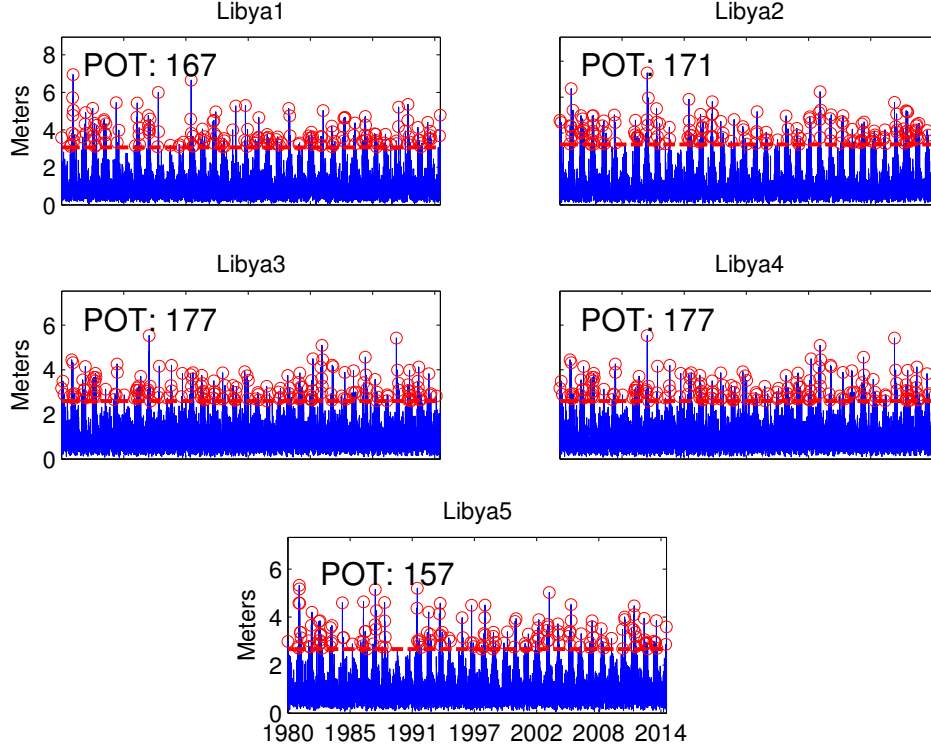


Figure 14: Declustered dataset of H_{m0}

331 The return levels (return periods) can be calculated by utilizing the fitted
 332 GPD parameters of each location and based on the procedure presented in
 333 Eq. 7. Since most wave applications are to be installed in a location for at
 334 least 20 years, we examined the return periods for H_{10} , H_{20} , H_{50} and H_{100}
 335 years, keeping in mind that any potential re-powering and re-use of a site
 336 might be possible.

$$\lambda_u = \frac{k}{n_{years}} \quad (6)$$

$$z_p = u + \frac{\hat{\sigma}}{\xi} \left[(N \cdot \lambda_u)^\xi - 1 \right] \quad (7)$$

337 with N return value in years, λ_u rate of threshold, u threshold, κ length
 338 of dataset by POT, n_{years} sample duration, $\hat{\sigma}$ (scale) and ξ (shape) the GPD
 339 parameters.

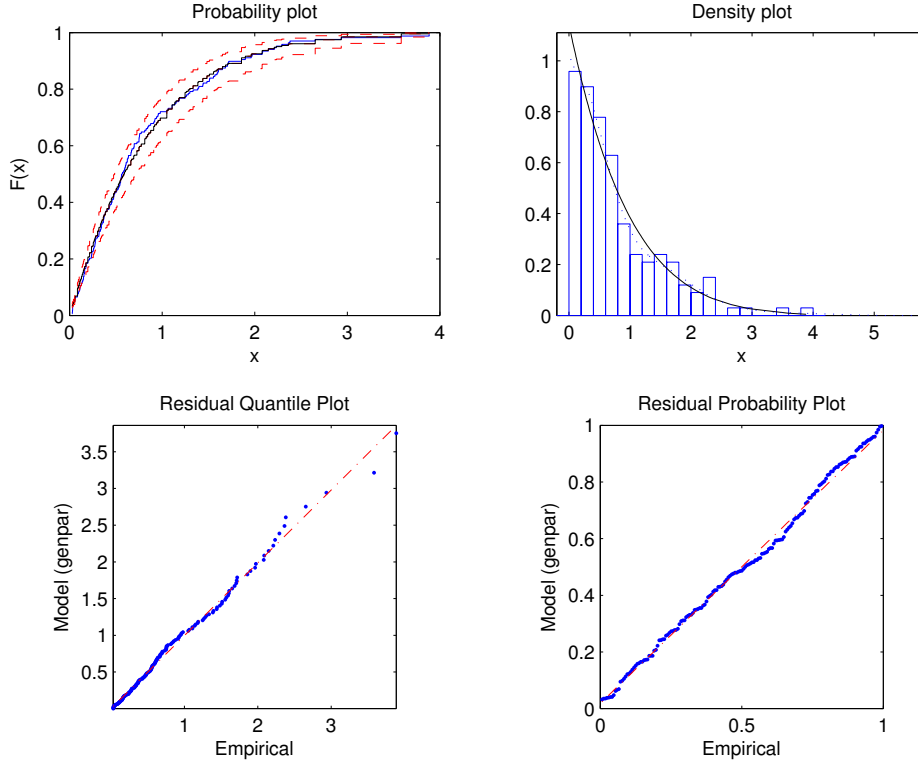


Figure 15: Diagnostics plots for fitter Libya 1

340 Probability and QQ plots are the bottom two plots in each graph. The
 341 GPD through the CDF (upper left plot of each graph), has a good fit while the
 342 histogram of the data is given in the upper right plot showing the distribution.
 343 The QQ plot (bottom right plot) for all GPD approaches has a good fit,
 344 adding confidence in the GPD method. From GPD parameters the return
 345 periods can now be estimated and compared with the annual maximum of
 346 the each location.

347 Based on the estimated return periods the most severe condition is met
 348 at Libya 2, followed by Libya 5 and 1. Interestingly Libya2 and 3, which
 349 exhibit a good wave energy content have lower return values. This indicates
 350 that the potential infrastructure costs may be less for the locations, reducing

Table 3: Return H_{m0} in meters

Location	H_{10}	H_{20}	H_{50}	H_{100}	H_{max}
Libya1	7.27	8.24	9.63	10.78	6.94
Libya2	8.62	9.97	12.03	13.82	7.34
Libya3	5.55	6.18	7.06	7.76	5.53
Libya4	5.55	6.18	7.06	7.76	5.53
Libya5	6.81	7.87	9.47	10.84	5.32

the potential capital expenditures required for strengthening works. Our findings show similar trends in extreme return periods with [45], however in that case the model used was an oceanic for a 10 years hindcast. The numerical modelling approach followed by our model allows greater outreach and higher fidelity in nearshore areas. Our return periods, though so good agreement with our H_{10} being over-estimated by $\approx 3\%$. Remaining return periods are higher in Arena et al. [45] in regards to our results from $\approx 1-9\%$.

4. Conclusions

In this study, a third generation wave numerical model was used, fed with high-resolution temporal and spatial data to examine the wave resource and potential wave power at Libyan coast for construction of a comprehensive wave power Atlas. A gap in the awareness of the local metocean conditions is evident by lack of appropriate resource assessment, this study tries to mitigate and provide with valuable information. The hindcast was based on a nested approach the wave numerical model validated [12, 13].

The wave assessment presented annual mean and maximum, quantifying the level of wave energy. The energy content is higher in winter months, with values for 8-10 kW/m . The Western coastlines, for example between 20-24° East, are exposed to higher resources, while region in encapsulated region such as the Gulf of Surt have almost three times less. However, the lower wave energy resource benefits from low coefficient of variation, enhancing the predictability for energy production. This can provide reliable predictions in energy production, thus reducing uncertainties.

The classification of sites shows that lower resources are encountered, favouring for selection of "low" operational WECs. Return value analysis shows that the probable severe waves are within $\approx 7-13m$ (depending on location), this may lead to considerations for cost reductions in the installa-

tion of WECs. The 35 years Atlas provides a thorough resource assessment and subsequently can be used to quantify potential production by wave converters.

Nearshore waters in Libya are not as energetic as the Atlantic coasts. However, they still hold a significant amount of renewable energy that can be harnessed. With financial support schemes by major banking institutions, developing industrial sectors and potential cooperation in the area, innovative solutions can aid in the energy and financial growth of the countries.

The nature of wave energy and the combination with other local indigenous resources, can lead to the diversification and energy targets set by the respective countries presented. While solar and wind, seem to be the more obvious solution, wave energy can act as an additional production mechanism to enhance RE production and reduce renewable intermittent production. In addition, growth for local coastal populations and industries is also a thing to be expected.

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